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GEOTHERMAL CONTROL ON FLOW PATTERNS IN THE LAST GLACIAL MAXIMUM ICE SHEET OF ICELAND

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ABSTRACT

Because it is located both on the Mid-Atlantic Ridge and on a mantle plume, Iceland is a region of intense tectonics and volcanism. During the last glaciation, the island was covered by an ice sheet approximately 1000 m thick. A reconstruction of the ice flow lines, based on glacial directional features, shows that the ice sheet was partly drained through fast-flowing streams. Fast flow of the ice streams has been recorded in megascale lineations and flutes visible on the currently deglaciated bedrock, and is confirmed by simple mass balance considerations. Locations of the major drainage routes correlate with locations of geothermal anomalies, suggesting that ice stream activity was favoured by lubrication of the bed by meltwater produced in regions of high geothermal heat flux. Similar control of ice flow by geothermal activity is expected in ice sheets currently covering tectonically and volcanically active area such as the West Antarctic ice sheet. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: ice stream; volcanism; heat flux; rift; Iceland; Antarctica

INTRODUCTION

The dynamics of ice sheets depends on internal parameters, such as the mechanical and thermal properties of the ice, and on external boundary conditions. The external conditions are (1) the topography, (2) the nature of the bed, (3) the distribution of accumulation, ablation and temperature at the surface and (4) the geothermal heat flux at the base (Paterson, 1994). When past and present ice sheets are studied or modelled, proper attention is given to the topography, to the nature of the bed and to the atmospheric conditions (e.g. Marsiat, 1994; Clark *et al.*, 1996; Marshall *et al.*, 1996). In contrast, because the geothermal heat flux is measured with difficulty in glaciated regions, its effect on glacial flow is poorly known and is rarely taken into account (e.g. Ritz *et al.*, 1997; Jonsson *et al.*, 1998).

In tectonically and volcanically quiet regions, such as the Greenland and East Antarctica cratons, variations of geothermal heat flux in space and time are small and probably do not significantly affect glacial flow. However, there are major glaciated regions of the world that are also tectonically or volcanically active: tectonic control on glacier dynamics has been suggested in West Antarctica (Anandakrishnan *et al.*, 1998), East Antarctica (Lawver *et al.*, 1993), North America (Post, 1969) and South America (Diraison *et al.*, 1997).

In tectonically active regions, the mean geothermal heat flux can reach values up to four times greater than typical continental values. In addition to the overall high heat flux, local geothermal anomalies of kilometric size, exceeding the mean value by up to several orders of magnitude, can be associated with volcanoes (Björnsson, 1988; Blankenship *et al.*, 1993; Jonsson *et al.*, 1998). Contemporary examples suggest that these anomalies can strongly affect glacial flow. In Iceland, the central part of the Vatnajökull ice cap is partly drained towards ice cauldrons created by melting above subglacial geothermal areas (Björnsson, 1988;

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Jonsson *et al.*, 1998). The West Antarctic ice sheet, located above an active rift zone (LeMasurier and Thomson, 1990; Blankenship *et al.*, 1993), is drained by ice streams flowing much more rapidly than the surrounding ice (Bentley, 1987). The mechanisms that allow fast flow of ice streams and the factors controlling their spatial distribution remain obscure (e.g. Alley *et al.*, 1987; Bentley, 1987; Clarke, 1987; Anandakrishnan and Alley, 1997; Marshall and Clarke, 1997; Payne and Dongelmans, 1997). Along with other hypotheses, the fast flow of the West Antarctic ice streams has been related to deformation of a water-saturated till layer, with the necessary meltwater supply originating from a subglacial geothermal anomaly upstream (Blankenship *et al.*, 1993).

These examples show that tectonic or volcanic activity can significantly affect glacial flow. However, these effects cannot be constrained easily in currently glaciated regions, because the conditions at the base and the presence of tectonic or volcanic activity can be inferred only from indirect geophysical measurements (e.g. Blankenship *et al.*, 1993). It is therefore suitable to study an area of well known tectonic and volcanic activity, formerly covered by an ice sheet and currently deglaciated. In Iceland, tectonics and volcanism, due to lithospheric spreading at the Mid-Atlantic Ridge, occurred during the last glaciation beneath an ice sheet approximately 1000 m thick. From a reconstruction of the flow patterns of this ice sheet, and from simple calculations, we illustrate how ice dynamics can be controlled by the geothermal heat flux associated with tectonic and volcanic activity.

GEOLOGICAL SETTING

Iceland is an emergent part of the Mid-Atlantic Ridge located above a mantle plume (Vogt, 1974; Wolfe *et al.*, 1997). The direction of divergence between the North American and European plates is N110°E, and the half-spreading rate is 0·9 cm a^{-1} (DeMets *et al.*, 1994). At the present time, volcanism and tectonics due to lithospheric accretion occur in the Neovolcanic Zone, which connects the Reykjanes Ridge in the southwest, to the Kolbeinsey Ridge in the north (Figure 1). This area is covered by interglacial and subglacial volcanic formations younger than 800 ka. On both sides of the Neovolcanic Zone, the currently inactive external zone is made up of Tertiary basalts emplaced from 16 Ma to 800 ka. These basalts are affected by numerous normal faults and dykes trending NE to NNE (Moorbath *et al.*, 1968; Saemundsson, 1979).

The Neovolcanic Zone has been classically subdivided into three rift systems (Figure 1) (Saemundsson, 1979). The Western Volcanic Zone (WVZ) is the terrestrial prolongation of the Reykjanes Ridge. The Eastern Volcanic Zone (EVZ) lies 100 km farther east and extends from the Vestmann Islands in the south to the Vatnajökull glacier in the north. The Northern Volcanic Zone (NVZ) extends from the Vatnajökull glacier to the northern coast of Iceland. In addition, volcanism and tectonics are active in the Snaefellsnes peninsula in western Iceland. In the Neovolcanic Zone, lithospheric accretion is controlled by NNE-trending volcanic systems, generally comprising a central volcano dissected by a fissure swarm composed of tension fractures, normal faults and eruptive fissures (Saemundsson, 1978; Gudmundsson, 1998). Volcanic activity during the last glaciation is attested by the existence of numerous subglacial volcanoes, which display very characteristic morphologies and compositions (Kjartansson, 1966; Jones, 1969, 1970; Allen, 1979; Werner *et al.*, 1996). The location of these volcanoes shows that the eastern flank of the NVZ and the area located between the WVZ and the EVZ were active during glacial times (Bourgeois *et al.*, 1998).

THE WEICHSELIAN ICE SHEET

For the last 4 Ma, at least 20 glacial stages have affected Iceland (Einarsson and Albertsson, 1988; Geirsdottir and Eiriksson, 1994). The extent of the first glaciations was limited to the south-eastern part of the island, but, after 2·5 Ma, an ice sheet covered most of Iceland (Geirsdottir and Eiriksson, 1994). The last glaciation (Weichselian) probably began around 100 ka BP, culminated 21 ka BP at the Last Glacial Maximum (LGM), and ended around 10 ka BP (Einarsson and Albertsson, 1988; Norddahl, 1990; Ingolfsson, 1991).

Several lines of evidence have been used to estimate the extent of the ice sheet at the LGM. Terminal moraines, located at elevations of less than 100 m along the present-day coastline, have been related to deglaciation stages around 12–10 ka; they suggest a wider extent of the ice sheet at the LGM (Figure 2)

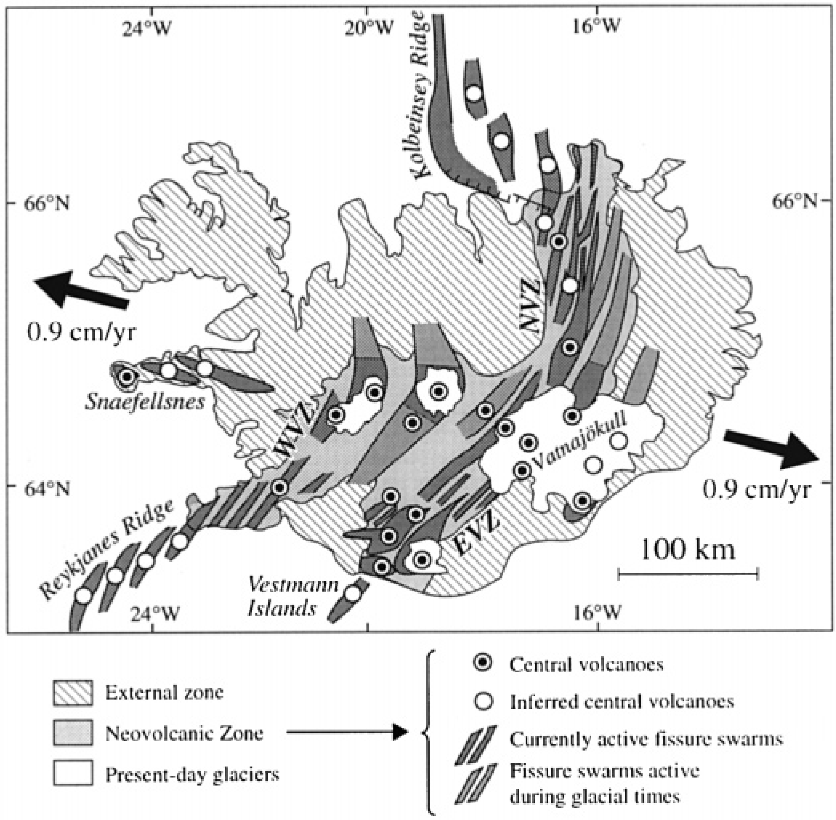

Figure 1. Geological setting. Iceland is a part of the Mid-Atlantic Ridge located between the Reykjanes Ridge to the southwest, and the Kolbeinsey Ridge to the north. At the present time, tectonic and volcanic activities occur in the Neovolcanic Zone, composed of three main branches, the Northern (NVZ), Western (WVZ) and Eastern (EVZ) Volcanic Zones. Within these zones, activity is located in fissure swarms associated with central volcanoes. During the last glaciation, the eastern flank of the NVZ and the region between the WVZ and the EVZ were also active

(Einarsson and Albertsson, 1988; Kaldal and Vikingsson, 1990; Norddahl, 1990; Ingolfsson, 1991; Geirsdottir *et al.*, 1997). Glacial coverage of the Iceland shelf is confirmed by the presence of glacial striae at sea level all along the coast and on Grimsey island, located 30 km to the north (Hoppe, 1982; Norddahl, 1990). On the shelf, 140 km west of Snaefellsnes, a ridge 25 to 30 m high and 800 m wide has been interpreted as being a terminal moraine, marking the maximal extent of the Weichselian ice sheet (Olafsdottir, 1975). At the edge of the shelf, Vogt *et al.* (1980) mapped glacially incised troughs filled by glacial sediments. For these reasons, the edge of the shelf, marked by the 200 m depth contour, is believed to have constituted the grounding line of the Weichselian ice sheet at the LGM (Norddahl, 1991). Down slope from the grounding line, the ice sheet turned into an ice shelf extending, at least during winter, over the whole Greenland–Norway–Iceland sea (CLIMAP Project Members, 1976).

The ice sheet, centred above SE Iceland, was drained by outlet glaciers disposed more or less radially between coastal nunataks (Figure 2). The nunataks, displaying a characteristic ‘alpine’ morphology, were covered by systems of valley glaciers, but their flat tops were not overlain by the main ice sheet (Sigbjarnarson, 1983; Norddahl, 1990, 1991). Vestfirdir peninsula, in the NW, was covered by a small independent ice cap (Hoppe, 1982).

The thickness of the ice sheet has been inferred from the elevations of the highest signs of glacial deposition or erosion and from the altitudes of subglacial volcanoes. In the southern and central parts of the island, its upper surface lay between 1500 and 2000 m in elevation. It decreased northwards, down to 300–500 m along the present-day coastline (Walker, 1965; Kjartansson, 1966; Einarsson and Albertsson, 1988;

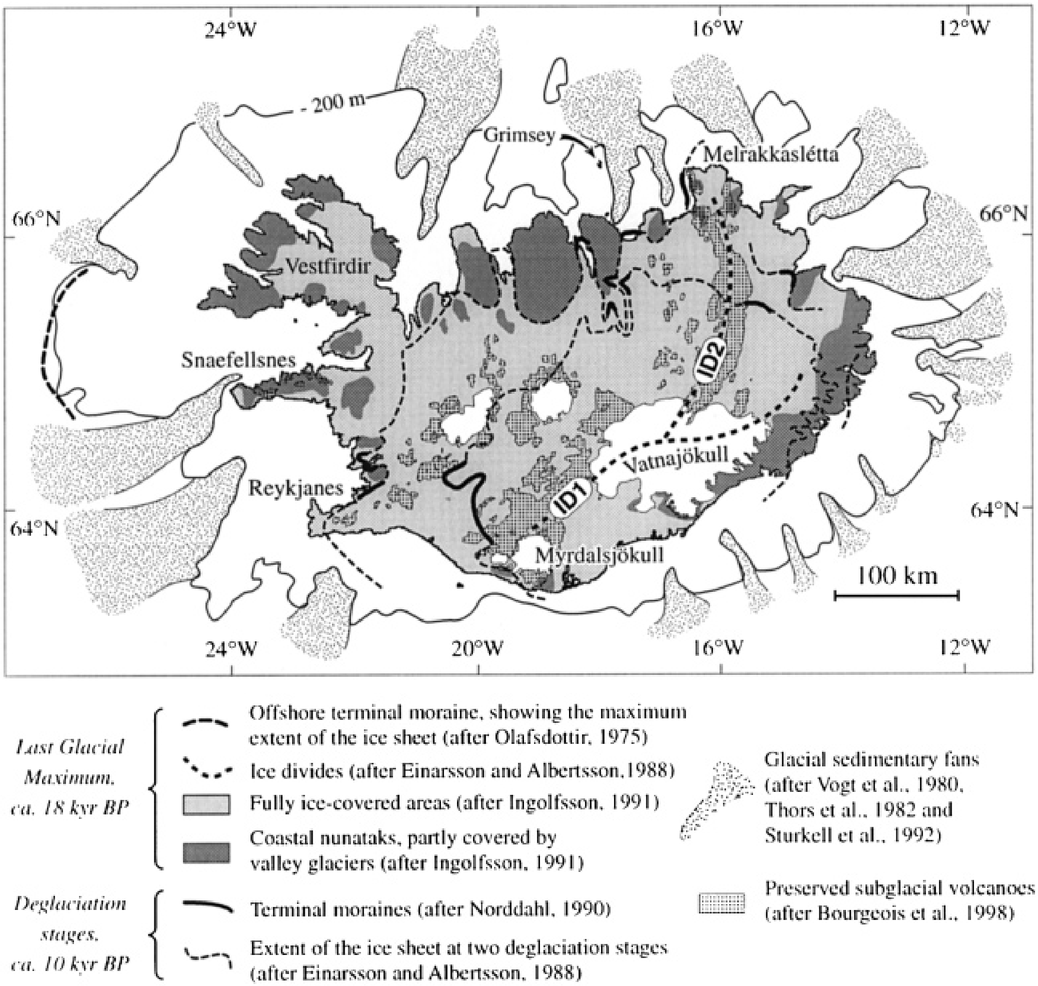

Figure 2. Extent of the Weichselian ice sheet. At the LGM, the ice sheet extended to the edge of the Icelandic shelf, marked by the 200 m depth contour. Some nunataks, partly covered by valley glaciers, remained in coastal areas. The main recognized ice divide (ID1) extended along the southeastern coast; a second one (ID2) extended northwards from Vatnajökull to Melrakkaslétta. Also shown are terminal moraines previously used to infer the extent of the ice sheet at two deglaciation stages, offshore glacial sedimentary fans, and preserved subglacial volcanic edifices

Norddahl, 1990, 1991). Locations of the ice divides have been inferred from directions of glacial striae (Einarsson and Albertsson, 1988; Pétursson, 1991). The main ice divide (hereafter referred to as ID1) passed through Myrdalsjökull and Vatnajökull, parallel to the southeastern coast of Iceland. A second one (hereafter referred to as ID2) extended northwards from Vatnajökull to Melrakkaslétta in the northeast. The flow of the ice sheet from the ice divides towards the sea has been little studied (Kaldal and Vikingsson, 1990; Norddahl, 1991). In order to determine the effect of geothermal heat flux on glacial flow, we have performed a reconstruction of former ice flow lines on the basis of glacial directional features.

FLOW PATTERNS OF THE ICE SHEET

Available data

To reconstruct the flow patterns of the ice sheet, we used several kinds of glacial directional features: striations, *roches moutonnées*, drumlins, flutes, megaflutes and ice-marginal moraines. The data set (Figure

3) includes glacial striae measured in the field, large-scale streamlined landforms observed on SPOT and Landsat images in northwest and north Iceland, and other data from the literature (Kjartansson, 1966, 1983; Saemundsson, 1977; Saemundsson and Einarsson, 1980; Hoppe, 1982; Sigbjarnarson, 1983; Johannesson *et al.*, 1990; Kaldal and Vikingsson, 1990; Norddahl, 1991; Pétursson, 1991). In addition, a digital elevation model (DEM), produced from the US Geological Survey files at 30 arcsec resolution, has been used to identify very large-scale landforms such as glacial valleys and nunataks.

Data consistency

Directional features mapped in Figure 3 seldom cross-cut each other. The more external ice-marginal moraines, corresponding to successive stages of deglaciation, are concentric and orthogonal to streamlined landforms and striae. This arrangement shows that no major change in flow lines occurred during the first deglaciation stages, whilst the ice sheet covered the whole island. Thus in a first approximation, the directional features can be considered to represent the flow lines of the ice sheet at its maximal stage.

The only exceptions are located in central Iceland: in this area, glacial directional features are arranged in distinct sets, which cross-cut each other (Figure 3). Southeast of Langjökull, a set of NW-trending flutes and striae, associated with NE-trending moraines, are oblique to the general SW trend of striae. Northeast of Langjökull, a set of NNE-trending flutes, associated with WNW-trending moraines, are oblique to striae trending NNW. These sets are related to late deglaciation stages, when the ice sheet had already receded to the most central part of Iceland (Kjartansson, 1966; Kaldal and Vikingsson, 1990).

Reconstruction of flow patterns

In central Iceland, we drew ice divides in regions where the streamlined landforms were divergent. North of Vatnajökull, the location of ice divides is poorly constrained by glacial directional data (Figure 3). However, the location of preserved subglacial volcanoes can be used as a proxy for the location of ice divides: volcanic products erupted beneath an ice sheet are generally removed by ice flow as eruptions proceed, but are preserved beneath ice divides thanks to slow ice motion (Behrendt *et al.*, 1995; Bourgeois *et al.*, 1998). North of Vatnajökull, the location of ice divides inferred by Einarsson and Albertsson (1988) and by Pétursson (1991) is consistent with the location of preserved subglacial volcanoes younger than 0·8 Ma (Figure 2).

We drew flow lines at regular intervals from the ice divides towards the sea, following glacial directional features. Minor sets of streamlined landforms located in central Iceland and related to late deglaciation stages were neglected.

In coastal regions, the areas of alpine landscape (Figure 3), corresponding to nunataks, have been identified on the DEM. By comparison with current ice flow in Antarctica (see for example Bentley, 1987), the main ice sheet was assumed to flow around these nunataks, which behaved as emergent obstacles. Except in the Flatey Peninsula (northern Iceland, Figure 3), glacial valleys on the nunataks are arranged in individual radial systems centred at the summit of each nunatak. This arrangement shows that each nunatak had its own glacial system, whose dynamics were independent of the dynamics of the main ice sheet (Hoppe, 1982; Norddahl, 1991). We therefore considered the flow of glaciers on the nunataks independently from the flow of the main ice sheet: we assumed that alpine-type glaciers flowed radially away from nunatak summits, along present-day valleys, either to the sea, or until they joined outlet glaciers of the main ice sheet.

The map of flow lines for the whole ice sheet is presented in Figure 4. Because streamlined landforms reflect only the directions of sliding at the base of the ice, the overall flow, including internal creep, was probably slightly different from the proposed reconstruction. It should also be noted that the distribution of precipitation has not been taken into account in the reconstruction. Therefore, flow lines represent the direction of sliding at any given point of the map, but not the amount of ice flowing through this point.

Results

The two ice divides previously recognized by Einarsson and Albertsson (1988) and by Pétursson (1991) in south and east Iceland appear clearly (ID1 and ID2). Other ice divides extend from Reykjanes to Langjökull

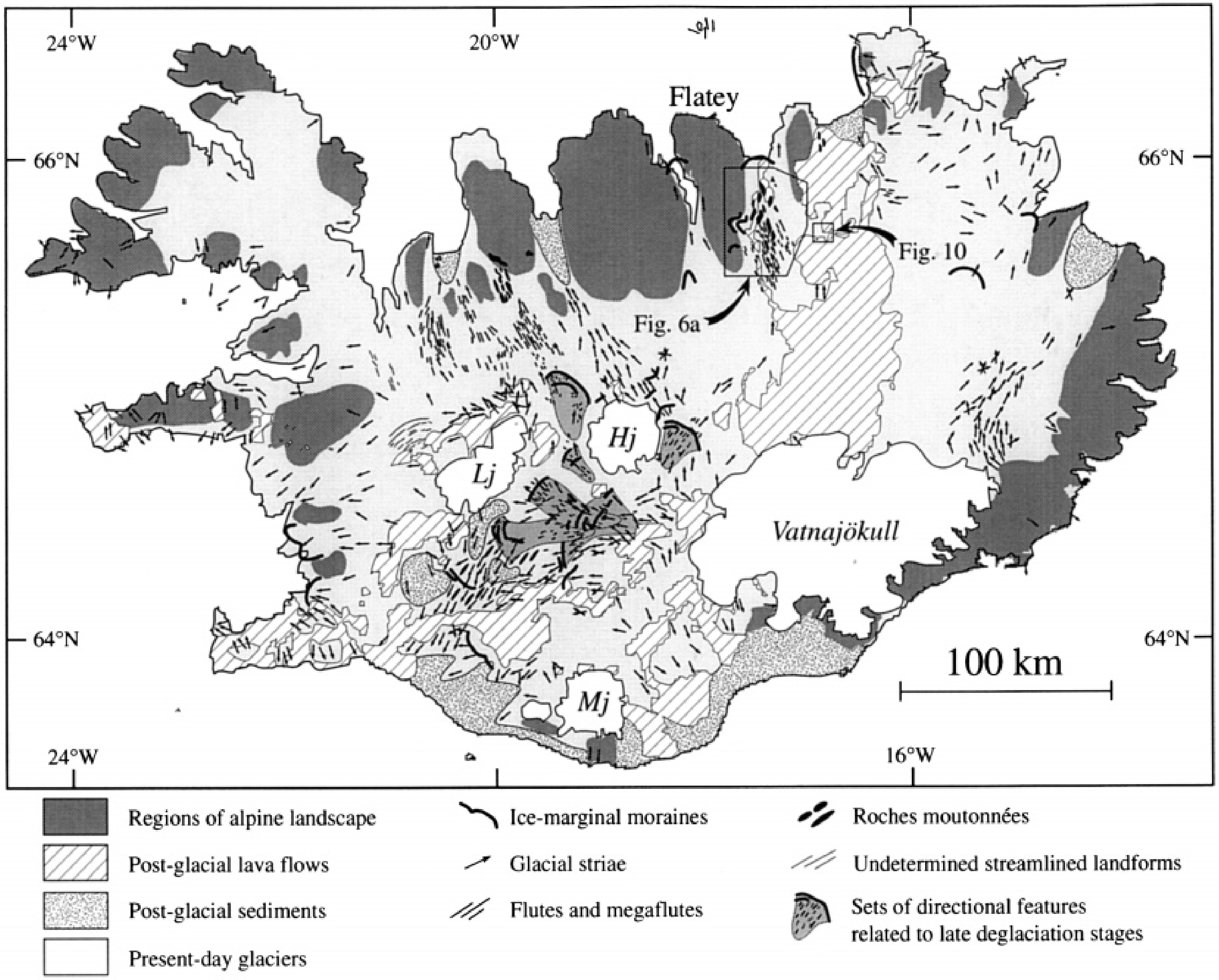

Figure 3. Map of glacial directional features used to reconstruct the flow patterns of the ice sheet (including new field data, data observed on SPOT and Landsat images, and field data from Kjartansson (1966, 1983), Saemundsson (1977), Saemundsson and Einarsson (1980), Hoppe (1982), Sigbjarnarson (1983), Johannesson *et al.* (1990), Kaldal and Vikingsson (1990), Norddahl (1991) and Pétursson (1991)). Boxes show the locations of Figures 6a and 10. Lj, Langjökull; Mj, Myrdalsjökull; Hj, Hofsjökull

(ID3), from Hofsjökull to Tröllaskagi (ID4), along Snaefellsnes peninsula (ID5) and on Vestfirdir peninsula (ID6) (Figure 4). For a minor part of the ice sheet, located southeast of ID1, flow lines are approximately parallel and trend southeastwards. Another part of the ice sheet, located east of ID2, flows northeastwards and is channelled in Héradsfloi and Vopnafjördur areas. The central part of the ice sheet is channelled between ID1–ID2 to the east, and ID3–ID4 to the west. It flows either southwestwards along the present-day Hvita river, or northwards through channels located in Axarfjördur and Skjalfandi. To the NW of ID3–ID4, the overall radial flow is channelled in Skagafjördur, Hunafloi, Breidafjördur and Faxafloi. The ice, which flows radially away from the top of Vestfirdir towards the sea, joins outlet glaciers of the main ice sheet in Breidafjördur and Hunafloi.

EVIDENCE FOR ICE STREAM ACTIVITY

A nearly circular ice sheet, as was the Weichselian ice sheet in Iceland, is expected to display a homogeneous pattern of radial flow from a more or less central area (e.g. Morland, 1997). Instead, in the reconstruction the ice sheet is drained through a number of narrow channels of parallel flow fed by convergent onset zones. The most prominent channels are those located in Skjalfandi, Axarfjördur and Hvita (Figure 4). They are bounded by two sets of parallel ice divides trending NE–SW (ID1–ID2 and ID3–ID4). Other channels are located in Faxafloi, Breidafjördur, Hunafloi, Skagafjördur, Vopnafjördur and Héradsfloi (Figure 4). Convergence of flow lines towards narrow channels of parallel flow strongly suggests ice stream activity. Geomorphological criteria for identifying ice streams in former ice sheets have been reviewed by Stokes and Clark (1999). Some of these criteria are:

1. Shape and dimension in map view (length $\geq$ 150 km, width $\geq$ 20 km, parallel margins, highly convergent flow patterns in the onset area).
2. Swarms of streamlined bedforms with a large length to width ratio.
3. Abrupt lateral margins, revealed by sharp zonation of landforms.
4. Evidence of pervasively deformed basal till.
5. Offshore sediment accumulation fans.

Two criteria should be considered in addition to those listed by Stokes and Clark (1999):

6. Shape of the upper surface of the hypothesized ice stream. Most present-day ice streams display a concave-up long profile and are characterized by low surface slopes and elevations, compared to the theoretical convex-up profile of ice sheets (Figure 5c) (Bentley, 1987). Reconstructing the long profile of the former ice surface on the basis of geomorphological data (lateral moraines, trim lines on nunataks, etc.) could thus help identify former ice streams.
7. Ice velocity. Present-day ice streams are arteries of fast-flowing ice (typically 200 to 1000 m a^{-1} (Bentley, 1987; Clarke, 1987)). Estimating former ice velocities could thus provide additional evidence for ice stream activity.

None of the criteria listed above is sufficient by itself to postulate the existence of ice streams. On the other hand, it would be highly unlikely that all of the criteria should have been preserved in one location and that a former ice stream should be identified unambiguously. However, the combination in one location of a number of the criteria should be indicative of ice stream activity (Stokes and Clark, 1999). We now use these criteria in order to determine whether flow channels of the LGM Icelandic ice sheet were ice streams.

Shape and dimension in map view

As stated above, the channels of parallel flow located in Skjalfandi, Axarfjördur and Hvita are fed by highly convergent onset zones at their heads (Figure 4). These channels are approximately 20 km wide, which fits with the typical width of present-day ice streams. Their minimal length, measured from their head to the present-day coastline, is approximately 100 km. If the channels are assumed to have reached the edge of the

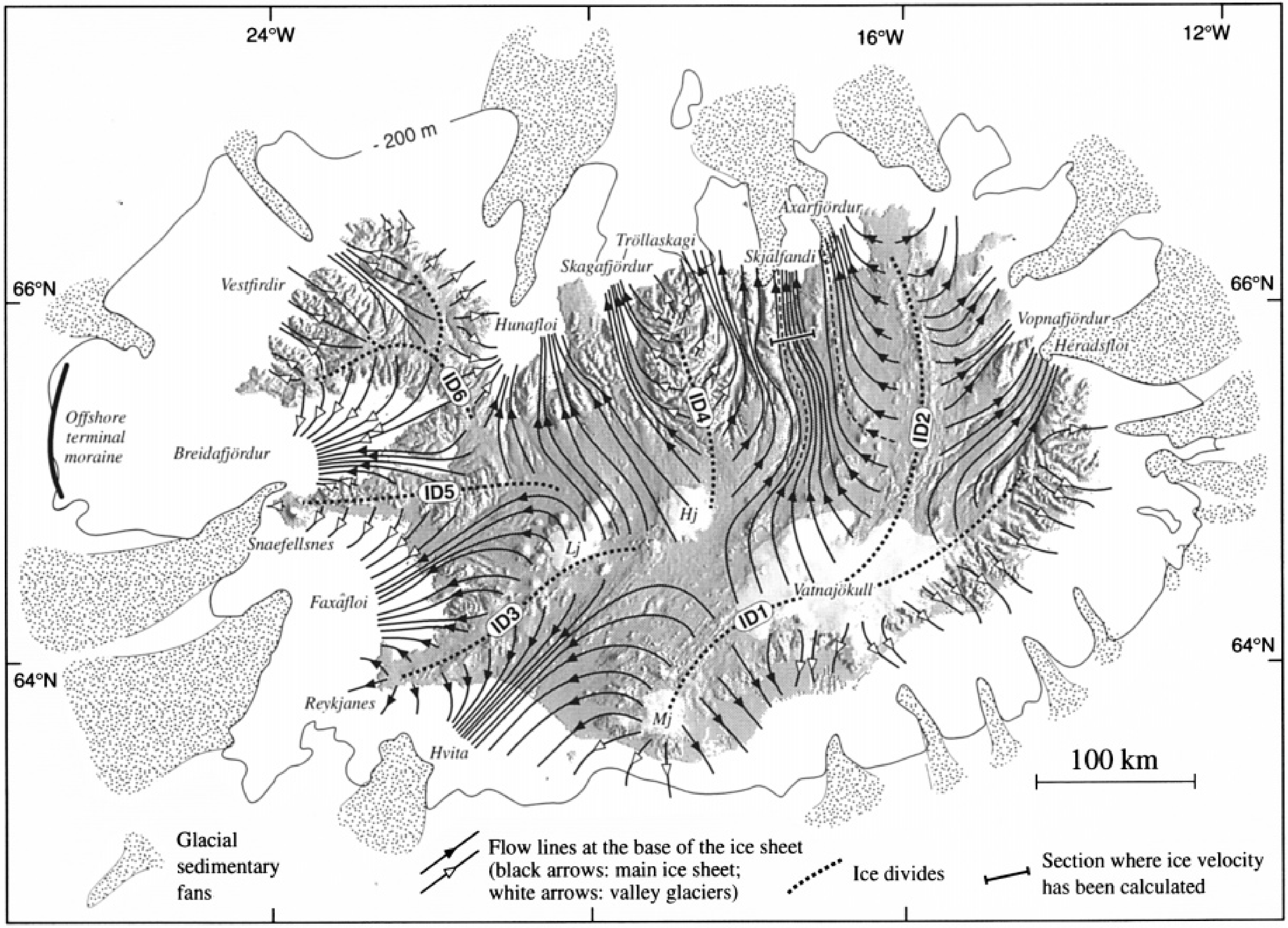

Figure 4. Reconstruction of the flow patterns of the ice sheet. Background: artificially shaded digital elevation model (DEM) established from US Geological Survey files at 30 arcsec resolution. The reconstruction is based on streamlined landforms mapped in Figure 3 and on large-scale glacial landforms (nunataks, glacial valleys) visible on the DEM. The main ice sheet (black arrow heads) has been distinguished from the valley glaciers flowing down from coastal nunataks (white arrow heads). In addition to the two ice divides formerly recognized on the eastern flank of the Neovolcanic Zone (ID1 and ID2), there are two other ice divides on its western flank (ID3 and ID4). The central part of the ice sheet is channelled between ID1–ID2 to the east, and ID3–ID4 to the west. It flows either southwestwards along the present-day Hvita river, or northwards through channels located in Axarfjördur and Skjalfandi. Other major ice routes are located in Héradsfloi, Vopnafjördur, Skagafjördur, Hunafloi, Breidafjördur and Faxafloi. Locations of off-shore glacial sedimentary fans (after Vogt *et al.*, 1980; Thors, 1982; Sturkell *et al.*, 1992) are consistent with locations of main ice routes. Stippled flow lines in Axarfjördur and Skjalfandi areas indicate locations of surface profiles shown on Figure 5

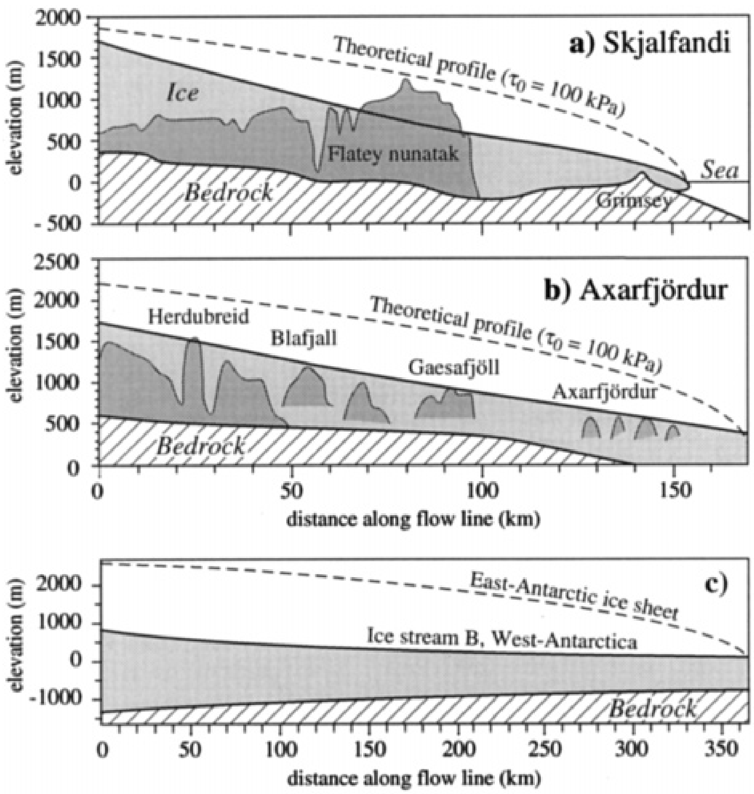

Figure 5. (a and b) Reconstructed profiles of the ice sheet in the Skjalfandi and Axarfjördur areas (locations shown by stippled flow lines in Figure 4; after Walker, 1965; Norddahl, 1991). The theoretical profile of a perfectly plastic circular ice sheet with a 200 km radius and a 100 kPa driving stress is drawn for comparison. (c) Surface profiles of Ice Stream B (West Antarctica) and of the East Antarctic ice sheet (after Bentley, 1987)

shelf (200 m depth contour; Figure 4), their length is approximately 150–200 km, which lies in the lower range of present-day ice streams. Channels located in Faxafloi, Breidafjördur, Hunafloi, Skagafjördur, Vopnafjördur and Héradsfloi display less convergent flow patterns and smaller sizes.

Surface shape

Norddahl (1991) used the highest signs of glacial erosion and deposition on nunataks to reconstruct the surface shape of the ice sheet in the Skjalfandi area. Walker (1965) used the elevation of subglacial volcanoes to reconstruct the surface shape of the ice sheet in the Axarfjördur area. Both reconstructions display a concave-up long profile (Figure 5a and b). The elevation of the ice surface is significantly lower than the theoretical profile calculated for a circular ice sheet with a 200 km radius and a 100 kPa driving stress. The reconstructed profiles are consistent with the surface shape of present-day ice streams (Figure 5c).

Ice velocity

Ice velocity can be estimated for the Skjalfandi channel from simple mass balance considerations (Figure 4). All the ice accumulating in the catchment basin above any section of the channel must be transferred downstream through this section. Steady-state velocity u through the section is then given by:

$$u = (bS)/(lh) \tag{1}$$

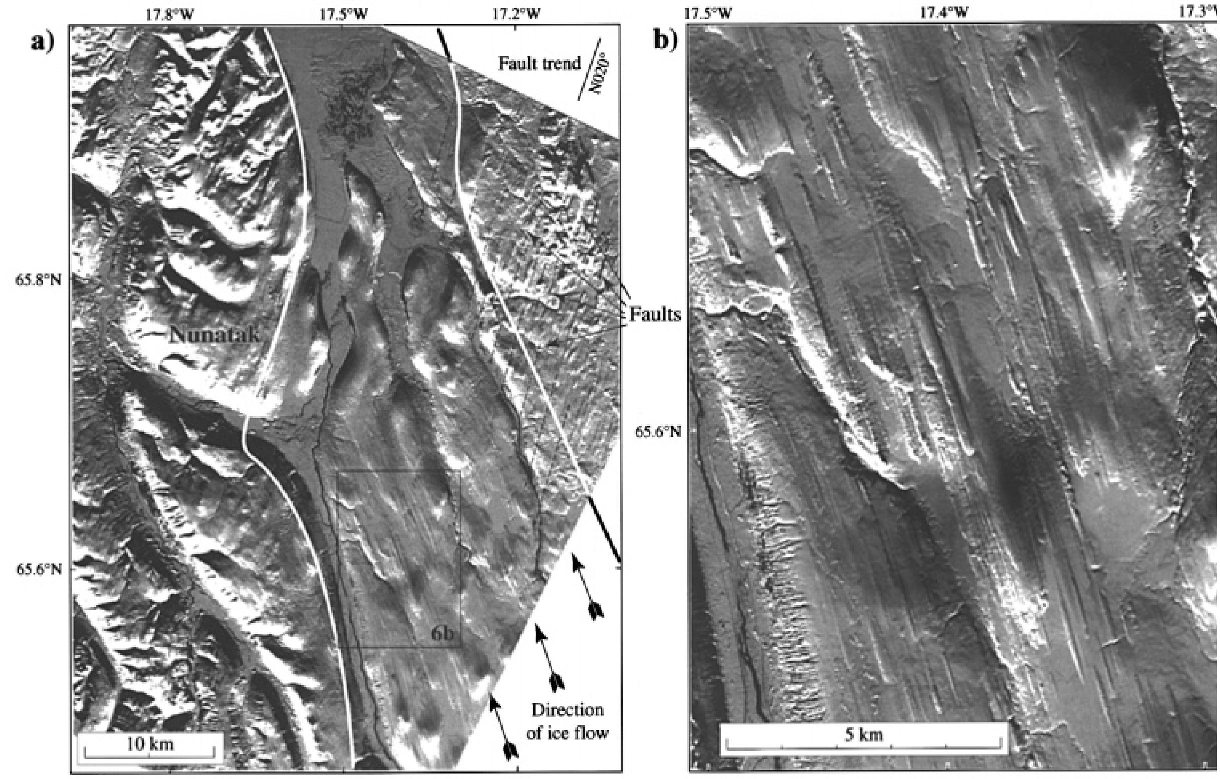

Figure 6. SPOT image (K–J: 714–214, date: 89/03/19, Panchromatic mode; location indicated on Figures 3 and 9), showing the bed of the Skjalfandi ice stream, on the western flank of the NVZ. The whole area is snow-covered. Relief is enhanced by low-angle sun illumination. (a) General view. Approximate margins of the stream are shown by white lines. The western flank is a nunatak, culminating at 1000 m elevation and deeply incised by glacial valleys. On the eastern flank, well preserved fault scarps trending NNE show that the basaltic bedrock has been little eroded. Scarcity of streamlined landforms suggests that this area was covered by nearly stagnant ice. In contrast, the bedrock beneath the stream has been heavily scoured. Former fault blocks, trending NNE, have been reshaped in the direction of ice flow. Elevation of the bed and of the eastern flank of the stream is 300 m. (b) Detailed view (location shown by box in (a)). Subglacial till is arranged in long, narrow flutes and mega-scale lineations, up to 5 km in length

where b is the mean balance (accumulation minus ablation) of the glacier above the section, S is the surface area of the catchment basin above the section, and l and h are the width and thickness of the channel (Clarke, 1987).

Elevations of nunatak bases indicate an ice thickness (h) of 500 to 600 m for the section indicated on Figure 4 (Norddahl, 1991). In this area, the channel width (l) is 20 km. The catchment basin has a surface area (S) of 8000 km^2. Numerical simulations indicate a mean balance (b) of 200 to 500 mm a^{-1} for central Iceland at the LGM (Pollard and Thompson, 1997). Taking these ranges of values, Equation 1 gives a velocity (u) of between 140 and 400 m a^{-1}. This high value is comparable to the velocities measured in the Greenland and West Antarctic ice streams. Highly convergent flow patterns suggest velocities of the same order of magnitude for the Axarfjördur and Hvita channels.

Bedforms and subglacial till deformation

A SPOT image of the bed of the former Skjalfandi channel is shown in Figure 6. The basaltic bedrock has been heavily scoured and displays numerous *roches moutonnées*. Networks of former faulted blocks in the basement, clearly visible on the eastern flank of the channel, have been intensively reshaped in the direction of ice flow beneath the channel (Figure 6a). The border between the area of intense erosion and the area where fault scarps are clearly visible is very sharp ($<$ 3 km wide).

Beneath the channel, the subglacial till is organized in long, narrow flutes and mega-scale lineations, up to 5 km in length (Figure 6b). Field observations reveal intense and spatially extensive deformation of the subglacial till. Deformation figures include subhorizontal shear bands, drag folds with subhorizontal axial planes, boudins, decollement surfaces and water escape figures (Bourgeois, 1998). These features indicate that the water-saturated subglacial till behaved as a decollement layer, allowing fast flow of the overlying ice.

Most parts of the beds of the Axarfjördur and Hvita channels are now covered by postglacial lava flows and sediments (Figure 3). However, in places where the glacial bed has not been concealed by Holocene formations, swarms of streamlined landforms with a large length to width ratio are visible on satellite images (Figure 3). Numerous flutes and megaflutes are also visible on the beds of the Hunafloi channels (Figure 3). These features, generally indicative of abundant basal meltwater, thin ice and fast flow, are consistent with ice stream activity (Clark, 1993, 1994; Bennett and Glasser, 1996).

Offshore sediment accumulation fans

Vogt *et al.* (1980) mapped several sedimentary fans of glacial origin at the edge of the shelf around Iceland (Figure 4). Seismic surveys also indicate 2 km thick sedimentary wedges at the mouths of Axarfjördur and Skjalfandi (Thors, 1982; Sturkell *et al.*, 1992). The most important fans are located downstream from ice flow channels (Figure 4). Though their ages and sedimentation rates are unknown, these fans provide evidence of focused accumulations of substantial sediment, which is consistent with ice stream activity.

The arguments listed above strongly suggest that the Skjalfandi channel was an ice stream. The highly convergent flow patterns in the onset areas of the Axarfjördur and Hvita channels and the wide spatial extent of their catchment basins suggest that these were also ice streams. However, streamlined bedforms and subglacial till deformation cannot be extensively observed on their beds because these regions are now concealed by postglacial lava flows and sediments. Though channels located in Faxafloi, Breidafjördur, Hunafloi, Skagafjördur, Vopnafjördur and Héradsfloi are less obvious candidates for ice streams, they undoubtedly were major drainage routes for the ice sheet.

DISCUSSION

External parameters controlling the direction and velocity of flow in an ice sheet are (1) the distribution of precipitation at the surface, (2) the bed topography, (3) the thermal conditions at the base and (4) the subglacial lithology. We now review these parameters in Iceland in order to determine how they can explain the reconstructed flow patterns and velocities.

Distribution of precipitation

Ice sheets flow from accumulation areas towards ablation areas. Hence locations of ice divides, and subsequently of drainage routes, can be controlled by locations of precipitation maxima. At the present day, oceanic and atmospheric circulation in the North Atlantic causes more abundant precipitation in the southern part of the island than in its northern part (Figure 7) (Björnsson *et al.*, 1979; Einarsson, 1988). Atmospheric and oceanic circulation obtained from climate reconstructions and numerical simulations suggests that this disparity also existed at the LGM (Figure 7) (CLIMAP Project Members, 1976; Sarnthein *et al.*, 1995; Ganopolski *et al.*, 1998). This disparity is consistent with the thickest part of the ice sheet being located in the south of the island (Walker, 1965; Einarsson and Albertsson, 1988; Pétursson, 1991). On the other hand, given the oceanic and atmospheric circulation at the LGM, there is no climatic reason for ID1 and ID3 to trend NE. The existence around ID2 of a precipitation maximum, shaped as a 250 km long and 50 km wide N–S trending stripe, is also unlikely. Flow patterns evidenced in the reconstruction cannot be explained solely by the distribution of precipitation.

Bed topography

If bedrock relief is sufficiently high with respect to ice thickness, it can play an important part in controlling the direction of ice flow. Similarity of elevations between the central plateau of Iceland and the

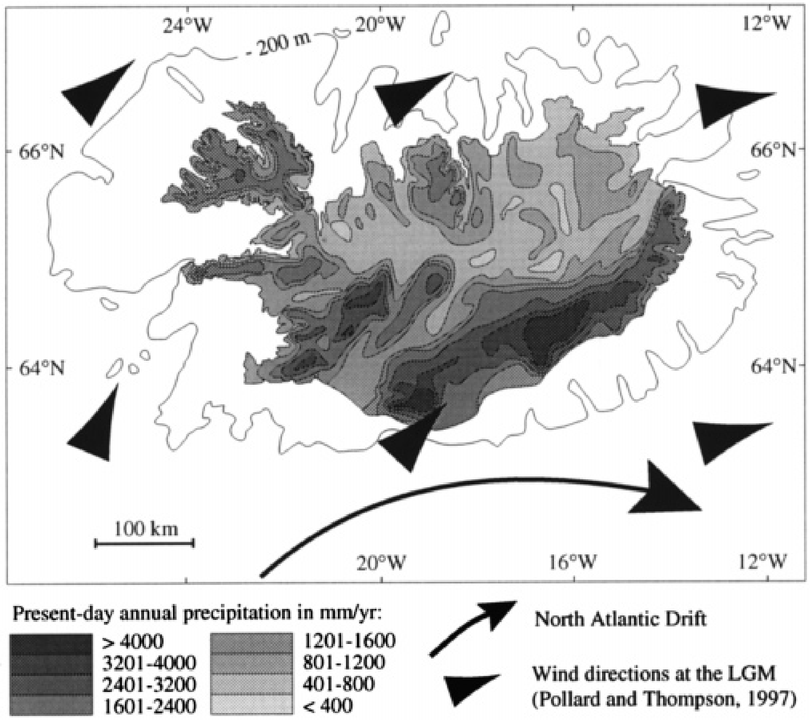

Figure 7. Present-day distribution of precipitation (Björnsson, 1979). Precipitation is very abundant in the southern part of the island, and decreases towards the north. Oceanic and atmospheric circulation obtained from climatic reconstructions (Sarnthein *et al.*, 1995; Pollard and Thompson, 1997) suggest that this disparity also existed at the LGM and was responsible for the location in south Iceland of the thickest part of the ice sheet

flat tops of coastal nunataks suggests that Iceland would constitute a rather flat dome extending to the sea if it had not been dissected by glacial erosion (Figure 8). High elevations on the eastern flank of the NVZ and in the EVZ are due to subglacial volcanoes resting on the basaltic basement (Figure 8). Because subglacial volcanoes, composed of unconsolidated basaltic breccia and hyaloclastites, are easily removed by ice flow, they cannot have controlled locations of ice divides (Bourgeois *et al.*, 1998).

In the north, the uplifted Tröllaskagi area departs from the general dome shape of the island (Figure 8). This uplifted area flanks the Skjalfandi ice stream. In contrast, the Axarfjördur and Hvita ice streams are not controlled by bedrock relief (Figures 4 and 8). Except for the locations of ID4 and of the Skjalfandi stream, which may be explained by high elevations in the Tröllaskagi area, the flow of the ice sheet and the location of the main ice routes cannot be explained solely by the initial bed topography.

Geothermal heat flux

The geothermal heat flux can affect glacial flow in two ways. First, the ice can flow towards geothermal anomalies because the ablation rate in these regions is increased by intense basal melting (Jonsson *et al.*, 1998). Second, meltwater production above geothermal anomalies can favour saturation and deformation of the subglacial till, thus creating channels of preferential flow for the ice (Blankenship *et al.*, 1993). A current example of such enhanced melting above a subglacial geothermal anomaly is the subglacial lake filling the Grimsvötn caldera, beneath Vatnajökull. The 50 W m^{-2} heat flux associated with the caldera is responsible for melting *c.* 8 m_{ice} a^{-1} on a surface area of 60 km^2. The meltwater accumulates for a few years in the lake, until it drains suddenly in a flood through subglacial channels (Björnsson, 1988).

A map of geothermal heat flux is presented in Figure 9. There are two kinds of geothermal anomalies in Iceland: (1) anomalies caused by circulation of warm groundwater, and (2) anomalies with a deep

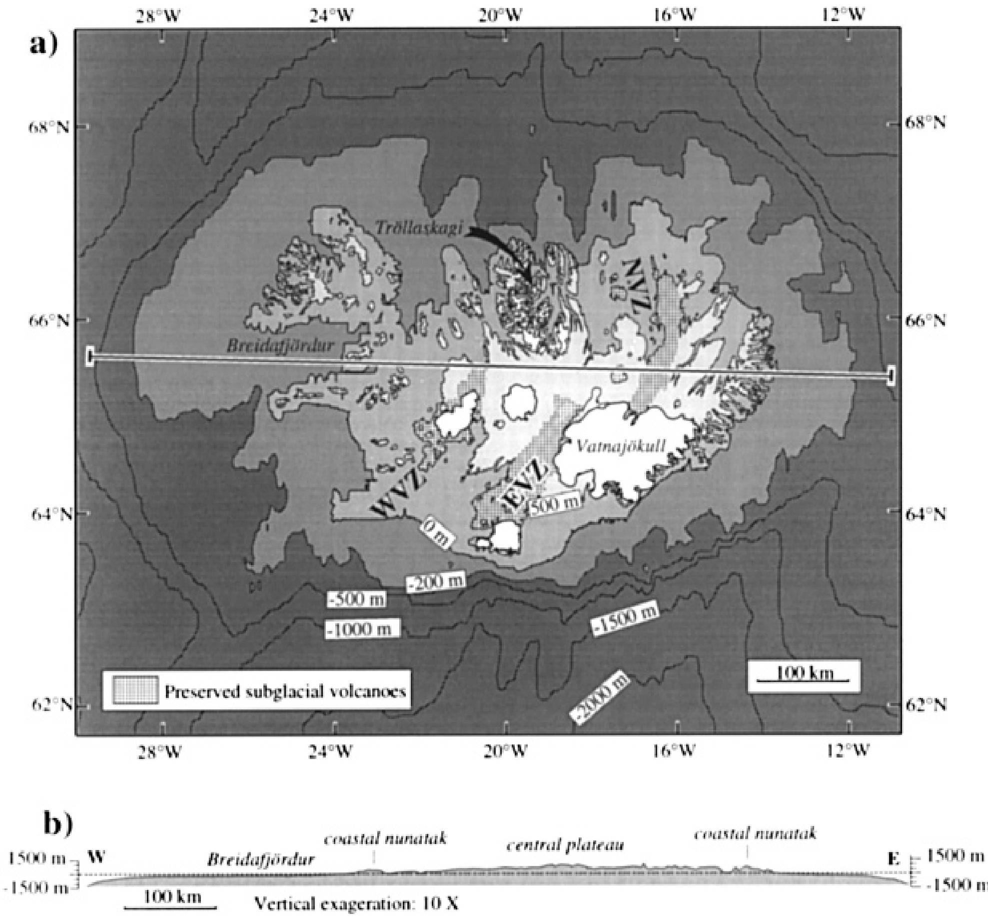

Figure 8. Topography of Iceland. (a) Topographic map. Elevation contours are drawn every 500 m, except for the −200 m contour, which marks the edge of the shelf. NVZ, Northern Volcanic Zone; EVZ, Eastern Volcanic Zone. (b) Topographic cross-section. Elevations are averaged on a 5 km wide interval along the line drawn in (a). The altitude of the flat tops of the coastal nunataks is comparable to the altitude of central Iceland (800–1200 m). Except for the glacially incised valleys; Iceland is a rather flat dome rising *c*. 2500 m above the surrounding ocean floor. The Neovolcanic Zone is poorly expressed in the topography

lithospheric origin (Flovenz and Saemundsson, 1993; Arnorsson, 1995a, 1995b). In order to avoid perturbations caused by water circulation, the presented map is based on values of geothermal gradient measured at carefully selected sites away from hydrothermal areas. Thus this map shows thermal anomalies with a deep lithospheric origin only (Flovenz and Saemundsson, 1993).

At first view, the conductive geothermal heat flux increases towards the Neovolcanic Zone, where it reaches its maximal values (Figure 9) (Palmason and Saemundsson, 1979; Flovenz and Saemundsson, 1993). Within the Neovolcanic Zone itself, because of the presence of a 500–1000 m thick permeable basalt formation at the surface, heat is mainly transported by thermal convection of geothermal water and is evacuated through discrete high-temperature hydrothermal fields. This results in an apparently low conductive heat flux between hydrothermal fields. However, the average heat flux in the Neovolcanic Zone has been estimated to be as high as 375 mW m^{-2} (Flovenz and Saemundsson, 1993). Heat flux values are low in the EVZ, compared to the WVZ and NVZ (Figure 9). In addition to the general pattern of increasing heat flux towards the Neovolcanic Zone, there are four major anomalies: one on each side of the WVZ, one in Breidafjördur in west Iceland and one in east Iceland (Figure 9).

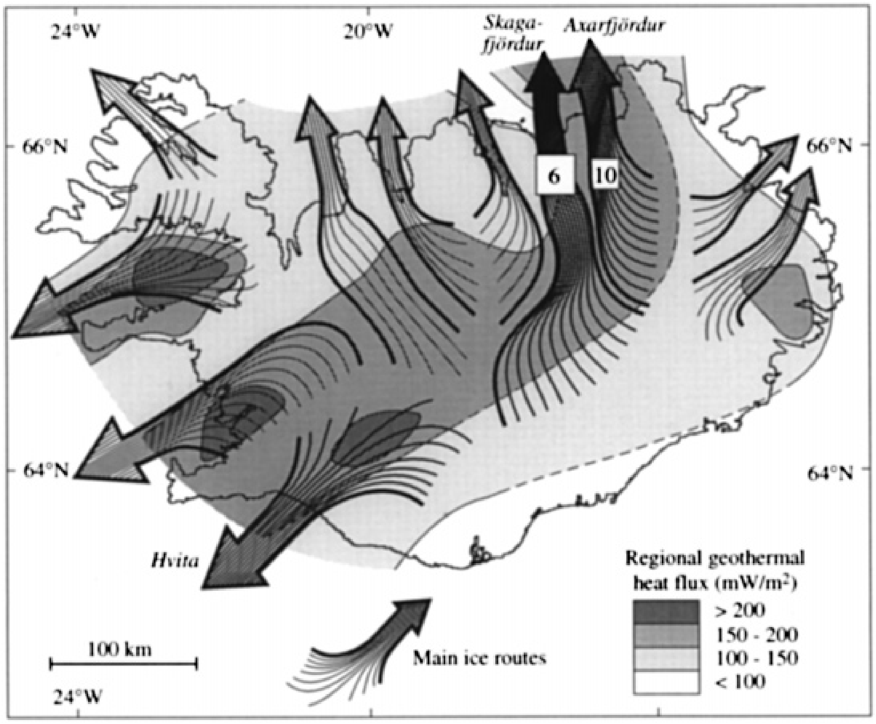

Figure 9. Correlation between flow patterns of ice sheet and geothermal heat flux. In order to avoid perturbations caused by circulation of warm water, the map of regional heat flux is based on values measured at carefully chosen sites away from hydrothermal areas (Flovenz and Saemundsson, 1993). The coincidence between location of main ice routes and location of thermal anomalies is striking. Locations of Figures 6 and 10 are shown by boxes

Comparison of reconstructed ice flow lines with the map of geothermal heat flux shows that positions of main ice routes correlate with locations of geothermal anomalies (Figure 9). The most probable ice streams (Skjalfandi, Axarfjördur and Hvita) were located in or close to the Neovolcanic Zone, where the geothermal heat flux reaches maximal values. A striking feature is the parallelism between the ice divides and the Neovolcanic Zone: ID1 and ID2 are on its eastern flank, ID3 and ID4 are on its western flank (compare Figures 1 and 4).

This spatial correlation suggests that the dynamics of the ice sheet was partly controlled by the geothermal heat flux. Enhanced ice melting above geothermal anomalies probably involved intense water production at the base of the ice sheet, thus favouring lubrication of the bed and controlling the location of major ice routes and ice streams.

Geomorphic evidence supports this interpretation: meltwater channels, up to 60 m deep, have been preserved in the NVZ, near the Krafla central volcano (Figure 10). The Krafla region is a very active geothermal area (Armansson *et al.*, 1987). Some of the channels are orientated transverse to the surface contours of the present-day topography, or have an 'up and down' long profile, which indicates that the channels are subglacial in origin. These channels give evidence of substantial ice melting in this area. Meltwater production was probably sufficient to allow initiation of ice stream activity in the Skjalfandi and Axarfjördur areas.

Subglacial lihology

Several studies have emphasized the importance of subglacial lithology on controlling the dynamics of ice sheets and the locations of ice streams. Constant supply of soft material from subglacial sedimentary basins

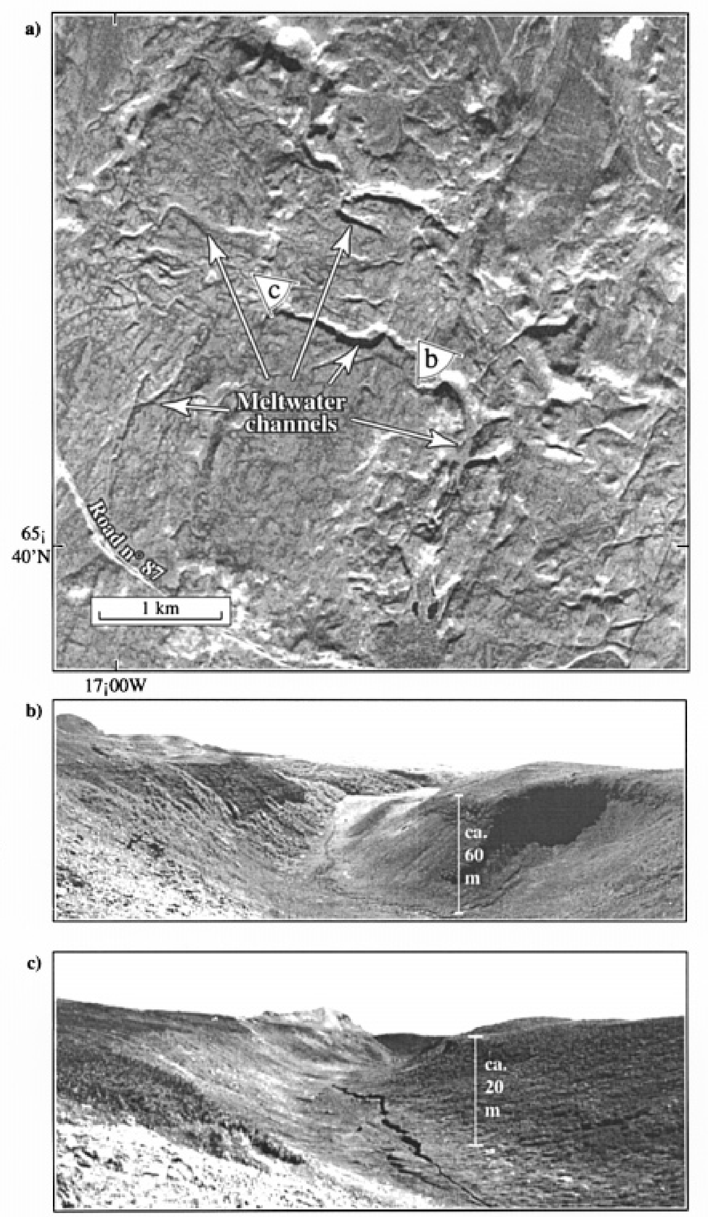

Figure 10. Subglacial meltwater channels near the Krafla volcano. (a) SPOT image (K–J: 717–214; date: 89/10/09; location indicated on Figures 3 and 9) showing part of the network. (b and c) Field photographs of two channels (angles of views shown in (a))

would be necessary to maintain a layer of deformable till beneath ice streams (e.g. Clark *et al.*, 1996; Anandakrishnan *et al.*, 1998; Bell *et al.*, 1998). There are no sedimentary basins in Iceland. Subglacial volcanoes, however, might constitute sources for recharging the subglacial till layer: subglacial eruptions produce large amounts of fine-grained basaltic breccia and glass shards (hyaloclastites), which are transported downstream by ice flow and by subglacial floods (Bourgeois *et al.*, 1998). Further study of the composition of the subglacial till beneath the inferred ice streams would be necessary to support this hypothesis.

CONCLUSIONS

Flow lines of the Weichselian ice sheet in Iceland have been reconstructed on the basis of glacial directional features. The reconstruction reveals the existence of channels of preferential flow and of fast-flowing ice streams. Mega-scale lineations and pervasively deformed subglacial till have been well preserved on the bed of some ice streams. Iceland thus provides a unique opportunity to study the bed of former ice streams.

Dynamics of the ice sheet were controlled by a combination of several parameters. More abundant precipitation along the southern coast was responsible for the location of the thickest part of the ice sheet in the south of the island. Major ice routes were located above areas of high geothermal heat flux. Ice streams, draining the central part of the ice sheet, were located in the Neovolcanic Zone. Formation of ice streams was favoured by high geothermal heat flux values and probably also by the availability of soft material produced by subglacial volcanic eruptions. Quantification of the relative importance of geothermal heat flux, topography, climate and availability of soft material on controlling the dynamics of the ice sheet would require numerical modelling. This work, however, shows that the geothermal heat flux is a first-order parameter of the dynamics of ice sheets. Similar control of ice flow by geothermal activity is strongly expected in ice sheets currently covering tectonically and volcanically active areas, such as the West Antarctic ice sheet (Blankenship *et al.*, 1993).

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